A Signal-Processing Framework for Inverse Rendering

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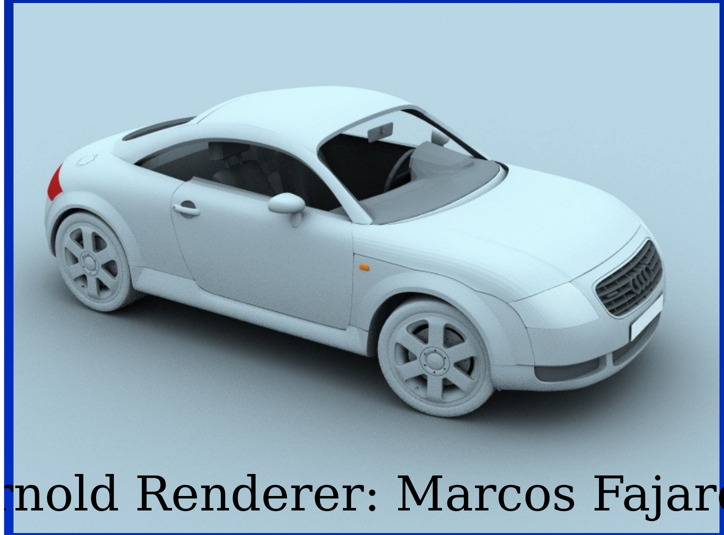
Photorealistic Rendering

Geometry

70’s, 80’s: Splines
90’s: Range Data

Rendering Algorit



Arnold Renderer: Marcos Fajardo

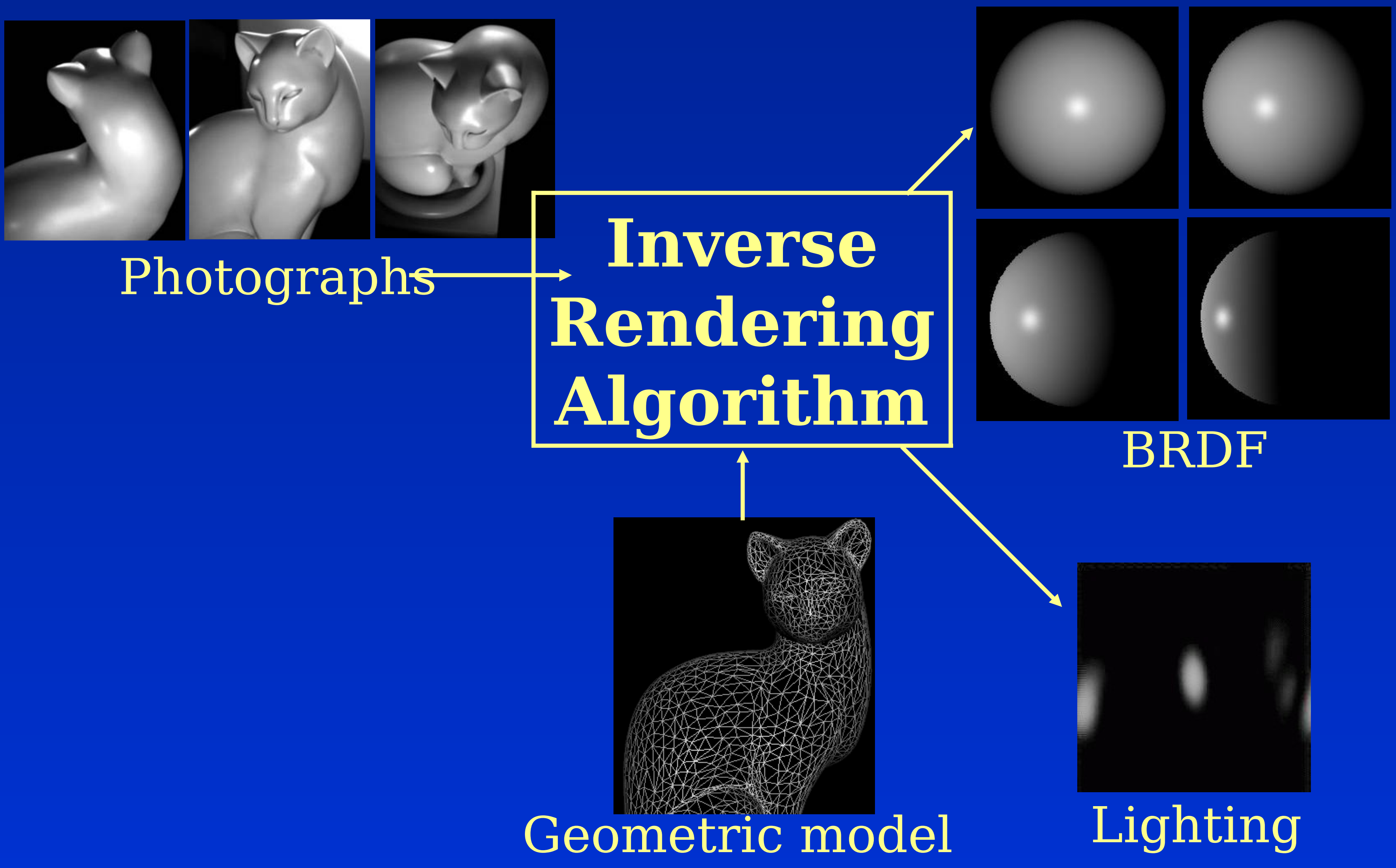
80’s,90’s: Physically bas

Materials/Lighting

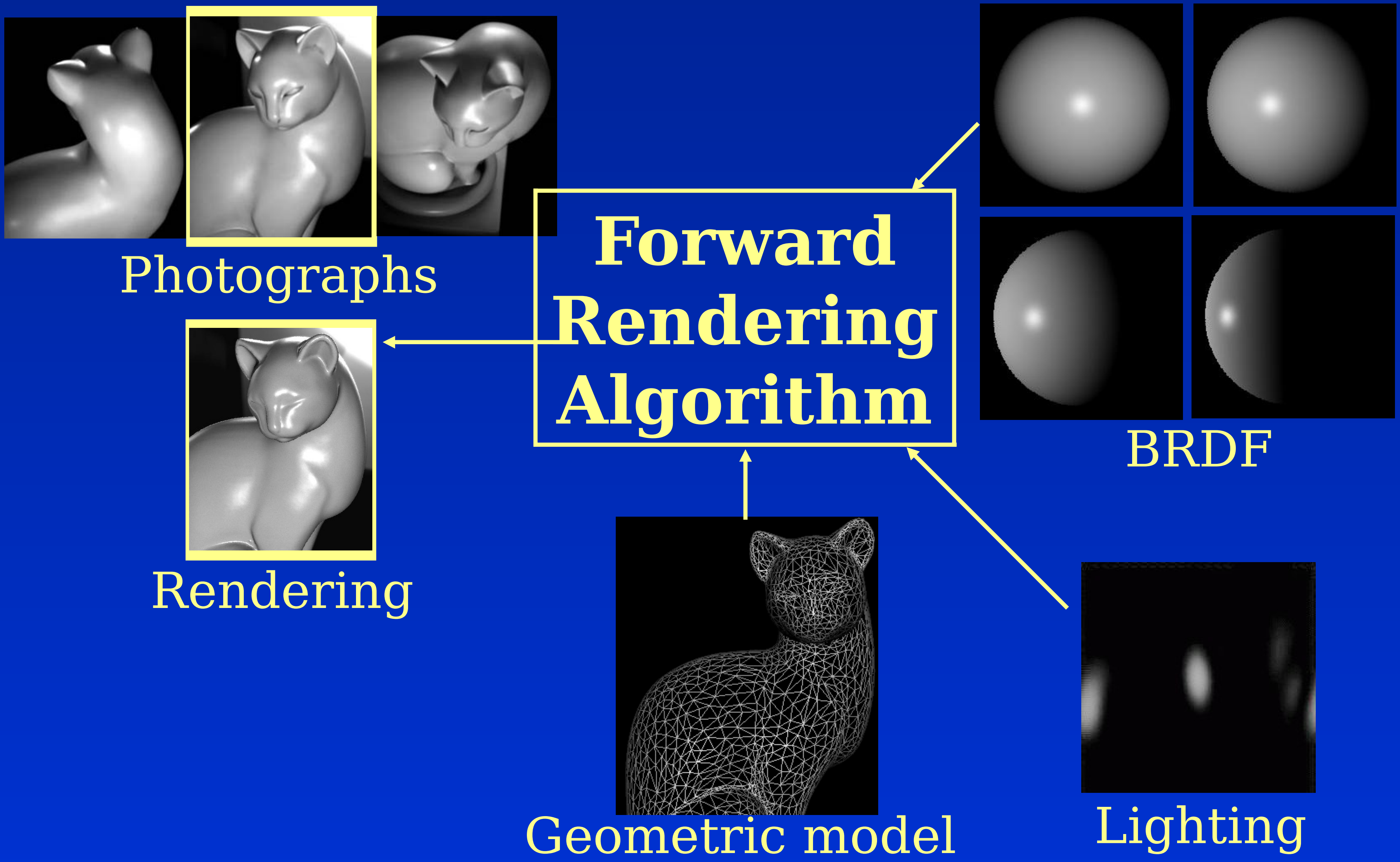
(Texture Reflectance[BRDF] Lighting)

Realistic input models

Flowchart


Photographs
Inverse Rendering Algorithm
BRDF
Geometric model
Lighting

Flowchart


Photographs
Forward Rendering Algorithm
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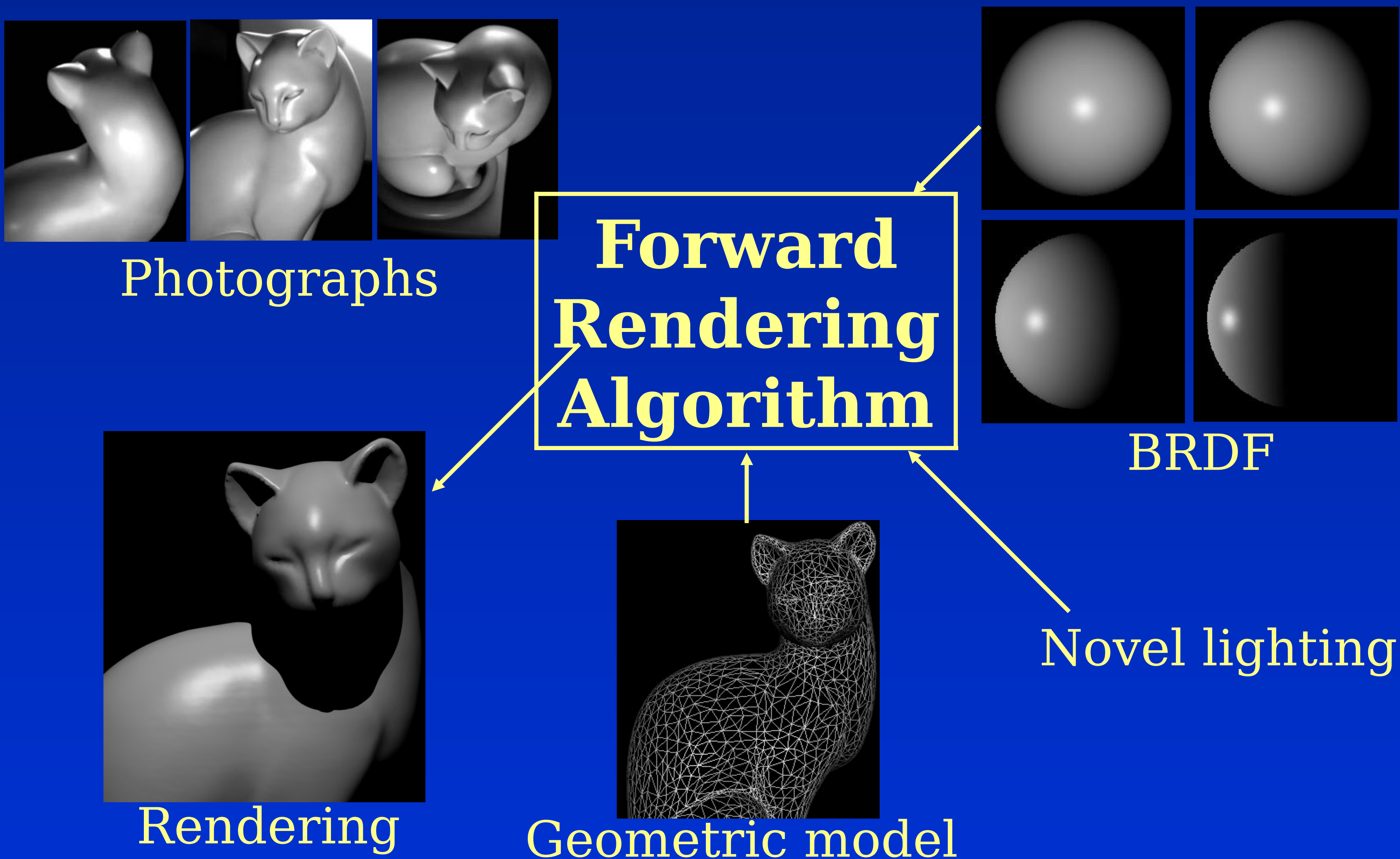

Photographs
Forward Rendering Algorithm
BRDF
Novel lighting
Rendering
Geometric model

Assumptions

- Known geometry
- Distant illumination
- Homogenous isotropic materials
- Convex curved surfaces: no shadows, interreflection

Later, practical algorithms: relax some assumptions

Inverse Rendering

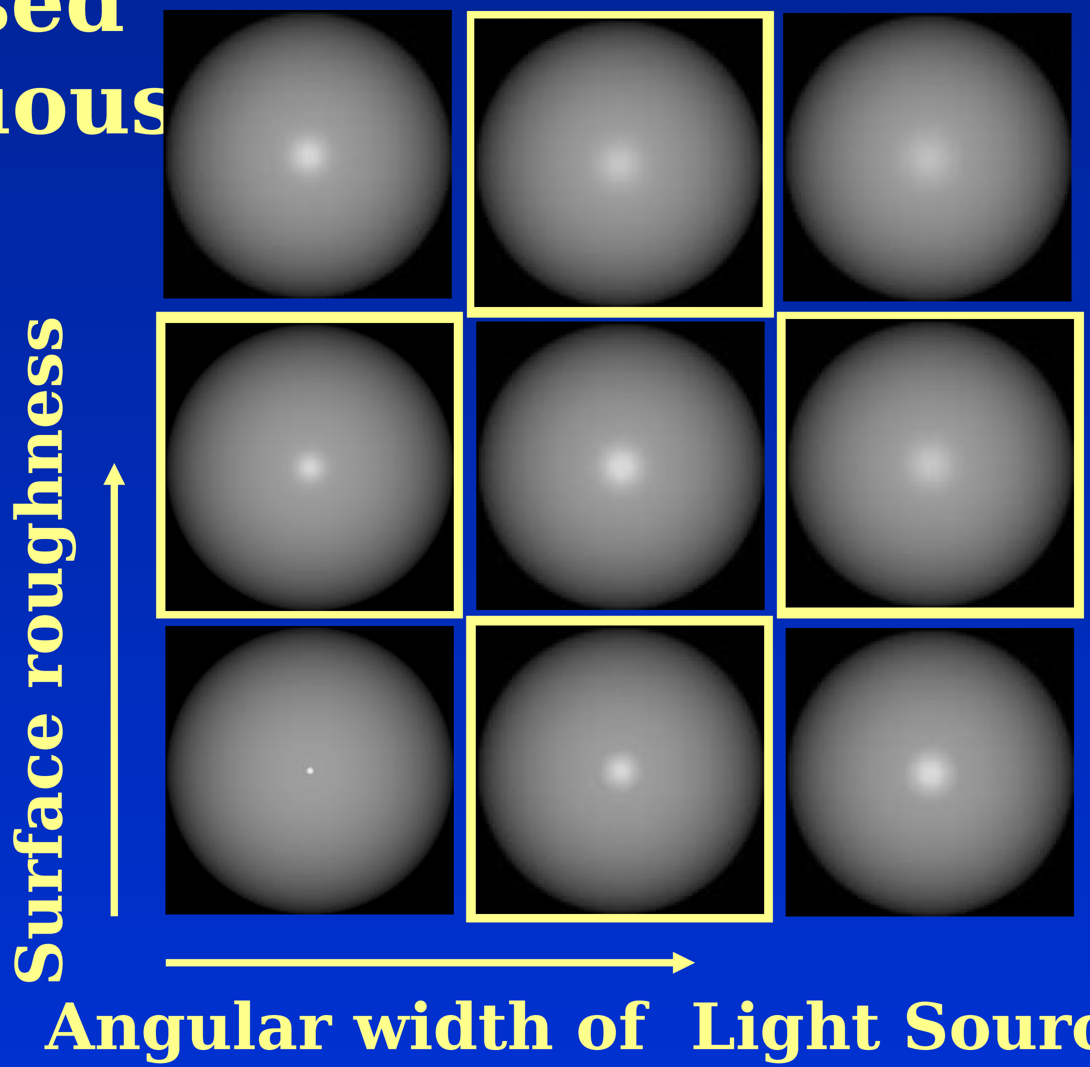
BRDF \ Lighting	Known	Unknown
Known		Miller and Hoffman 84 Marschner and Greenberg 97
Unknown	Sato et al. 97 Dana et al. 99 Debevec et al. 00 Marschner et al. 00	Sato et al. 99 Nishino et al. 01

Textures are a third axis

Inverse Problems: Difficulties

Ill-posed

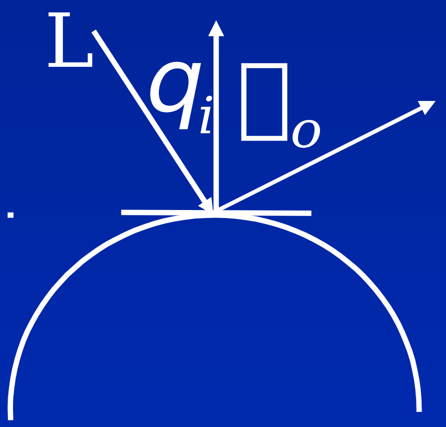
ambiguous

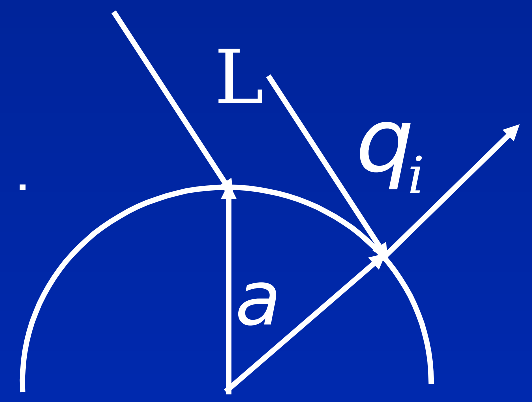


Contributions

1. Formalize reflection as convolution
2. Signal-processing framework
3. Analyze well-posedness of inverse problems
4. Practical algorithms

Reflection as Convolution (2D)



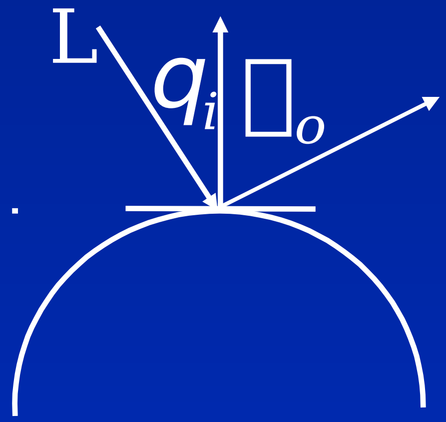


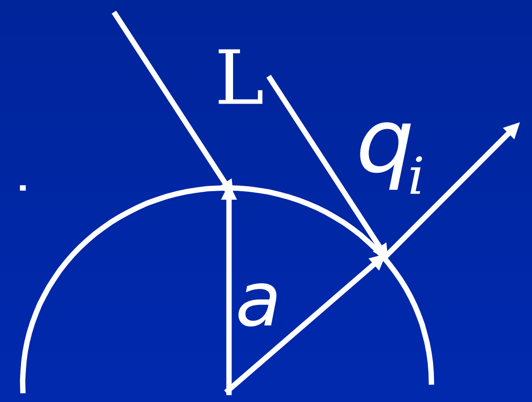
$$B(\theta_o) = \int_{-\pi/2}^{\pi/2} L(\theta_i)\, \rho(\theta_i, \theta_o)\, d\theta_i$$

Reflected Light Field **Lighting** **BRDF**

$$B(\alpha, \theta_o) = \int_{-\pi/2}^{\pi/2} L(\alpha + \theta_i)\, \rho(\theta_i, \theta_o)\, d\theta_i$$

Reflection as Convolution (2D)





$$B(\alpha,\theta_o) = \int_{-\pi/2}^{\pi/2} L(\alpha+\theta_i)\,\rho(\theta_i,\theta_o)\,d\theta_i$$

$$B = L \otimes \rho$$

Fourier analysis

$$B_{l,p} = 2\pi L_l \rho_{l,p}$$

Spatial: integral

Frequency: product

Spherical Harmonic Analysis

2D:

$$B(\alpha,\theta_o) = \int_{-\pi/2}^{\pi/2} L(\alpha+\theta_i)\;\rho(\theta_i,\theta_o)\;d\theta_i$$

$$B_{l,p} = 2\pi L_l \rho_{l,p}$$

3D:

$$B(\alpha,\beta,\theta_o,\phi_o) = \int_0^{\frac{\pi}{2}}\int_0^{2\pi} L(R_{\alpha,\beta}[\theta_i,\phi_i])\,\rho(\theta_i,\phi_i,\theta_o,\phi_o)\,d\theta_i d\phi_i$$

$$B_{lm,pq} = \Lambda_l L_{lm} \rho_{lq,pq}$$

Insights: Signal Processing

Signal processing framework for reflection

- Light is the signal
- BRDF is the filter
- Reflection on a curved surface is convolution

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Filter is Delta function : Output = Signal

Mirror BRDF : Image = Lighting

[Miller and Hoffman 84]

Image courtesy Paul Debevec

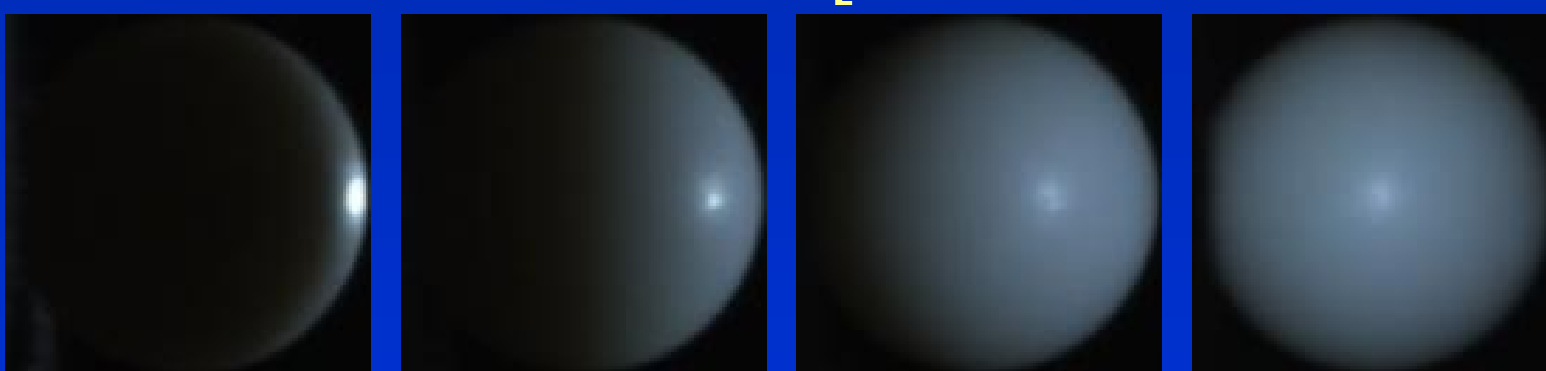
Insights: Signal Processing

Signal processing framework for reflection

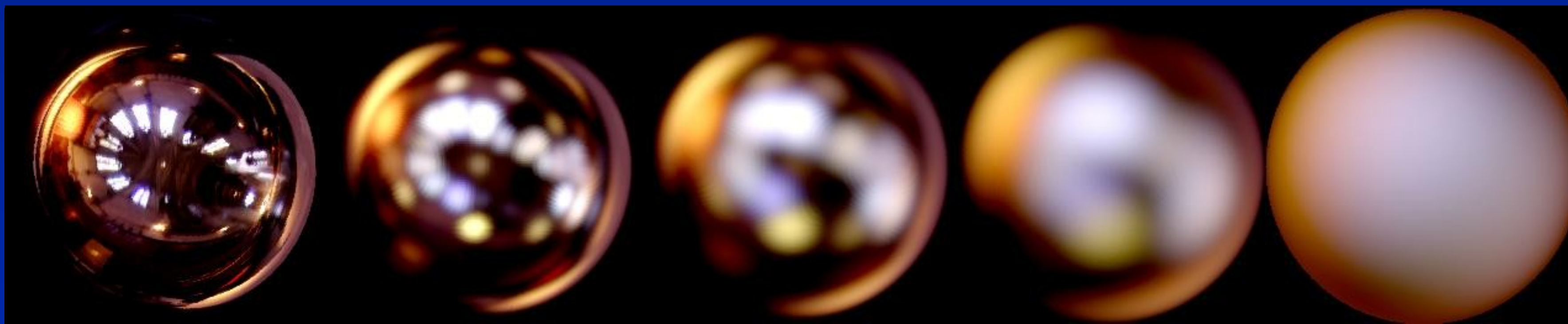
- Light is the signal
- BRDF is the filter
- Reflection on a curved surface is convolution

ignal is Delta function : Output = Filter

Point Light Source : Images = BRDF [Marschner et al. 00]



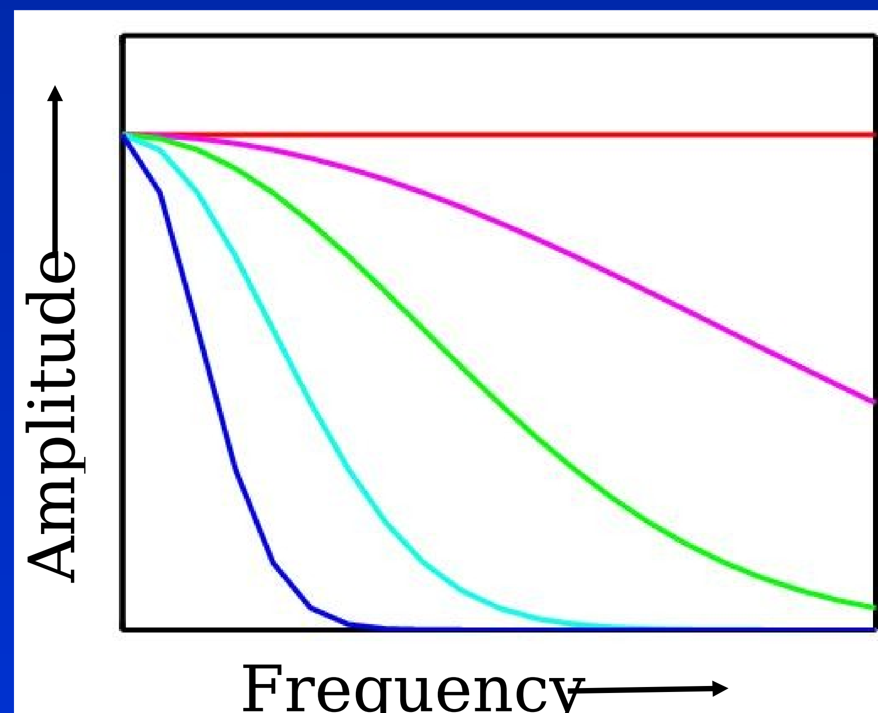
Phong, Microfacet Models



Mirror

Roughness

Illumination estimation
ll-posed for rough surfaces



Inverse Lighting

Given: B,ρ find L

$$B = L \otimes \rho$$

$$B_{lm,pq} = \Lambda_l L_{lm} \rho_{lq,pq}$$

$$L_{lm} = \frac{1}{\Lambda_l} \frac{B_{lm,pq}}{\rho_{lq,pq}}$$

Well-posed unless denominator vanishes

- BRDF should contain high frequencies : Sharp highlights
- Diffuse reflectors low pass filters: Inverse lighting ill-posed

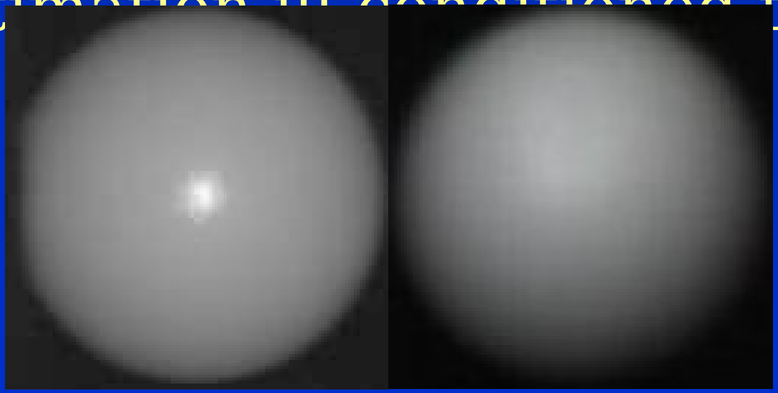
Inverse BRDF

Given: B,L find ρ

$$\rho_{lq,pq} = \frac{1}{\Lambda_l} \frac{B_{lm,pq}}{L_{lm}}$$

Well-posed unless L_{lm} vanishes

- Lighting should have sharp features (point sources, edges)
- BRDF estimation ill conditioned for soft lighting



Directio nal

Source

Area source

Same BRDF

Factoring the Light Field

Given: B find L and ρ

$$\underset{4D}{B} = \underset{2D}{L} \otimes \underset{3D}{\rho}$$

More knowns (4D)
than unknowns (2D/3D)

Light Field can be factored

- Up to global scale factor
- Assumes reciprocity of BRDF
- Can be ill-conditioned
- Analytic formula in paper

Practical Issues

- Incomplete sparse data (few photographs)
  Difficult to compute frequency spectra
- Concavities: Self Shadowing and Interreflection
- Spatially varying BRDFs: Textures

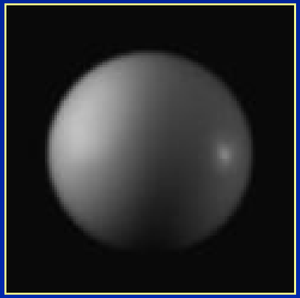
Practical Issues

- Incomplete sparse data (few photographs)
  - Difficult to compute frequency spectra
- Concavities: Self Shadowing and Interreflection
- Spatially varying BRDFs: Textures

Issues can be addressed; can derive practical algorithms
- Dual spatial (angular) and frequency-space representation
- Simple extensions for shadowing, textures

Algorithm Validation

Photograph



"True" values

K_d	0.91
K_s	0.09
μ	1.85
σ	0.13

Algorithm Validation

Photograph

Renderings

Known lighting

Unknown lighting

Image RMS error 5%

“True” values

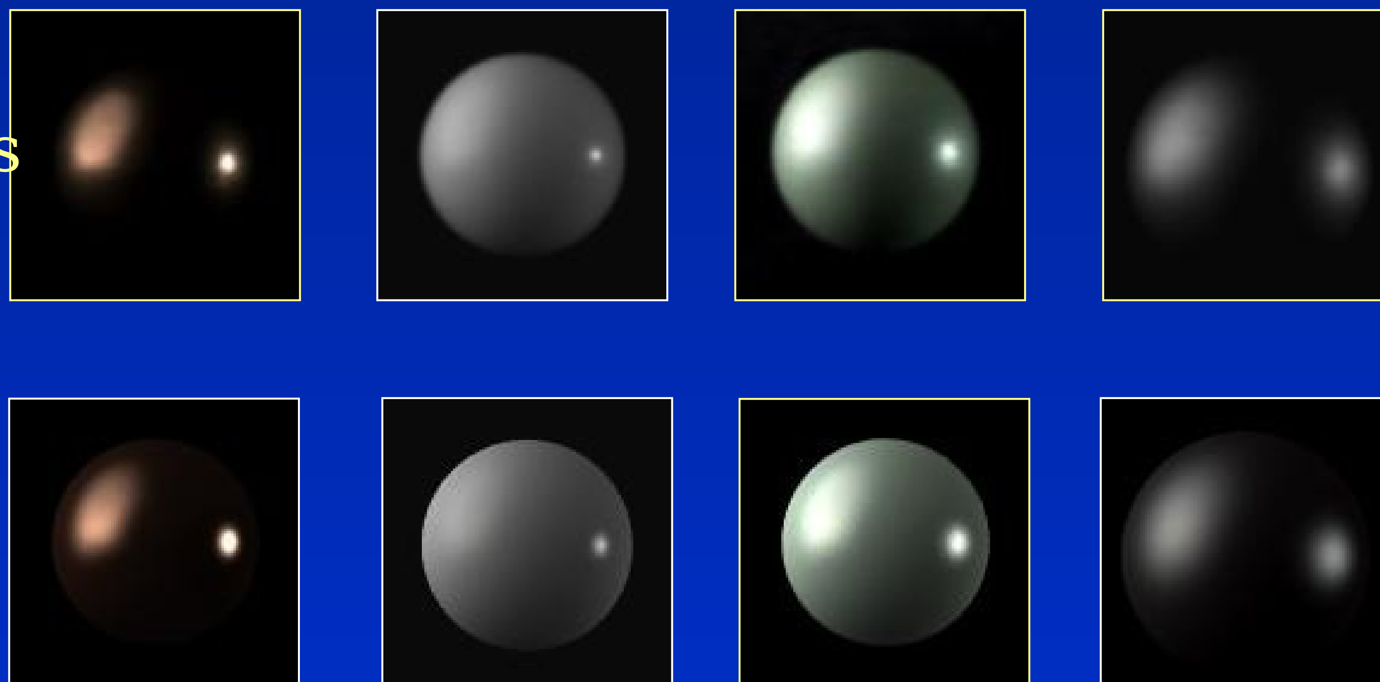
K_d	0.91	0.89	0.87
K_s	0.09	0.11	0.13
μ	1.85	1.78	1.48
σ	0.13	0.12	.14

Inverse BRDF: Spheres

Bronze Delrin Paint Rough Steel

Photographs

Renderings (Recovered BRDF)



Complex Geometry

3 photographs of a sculpture

- Complex unknown illumination
- Geometry known
- Estimate microfacet BRDF *and* distant lighting

Comparison

Photograph

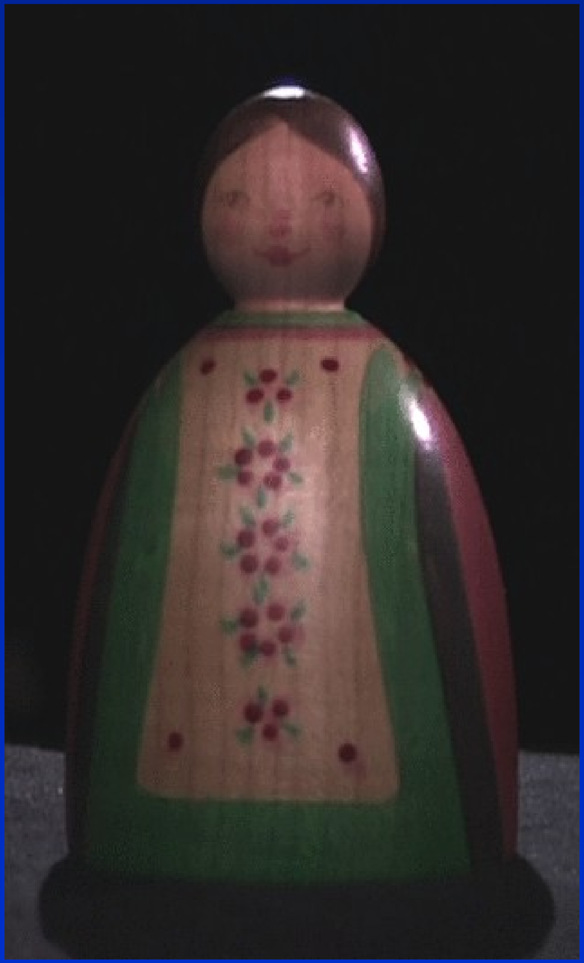
Rendering

New View, Lighting

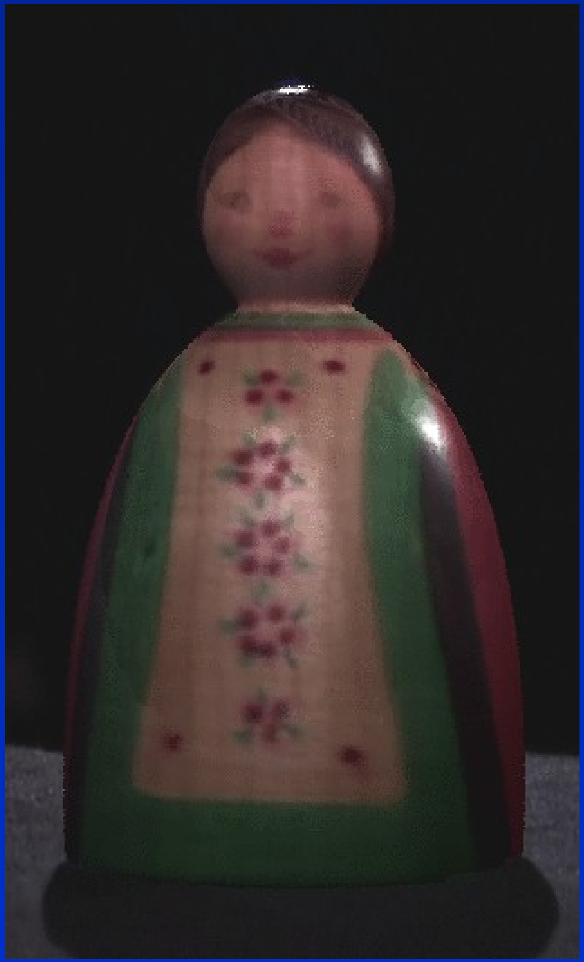

Photograph


Rendering

Textured Objects



Photograph



Rendering

Summary

- Reflection as convolution
- Signal-processing framework
- Formal study of inverse rendering
- Practical algorithms

Implications and Future Work

- Frequency space analysis of reflection
- Well-posedness of inverse problems
  - Perception, human vision
  - Forward rendering [Friday]
- Complex uncontrolled illumination

Acknowledgements

- Marc Levoy
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Paper Website:
http://graphics.stanford.edu/papers/invrend

The End

The End

Related Work

- Qualitative observation of reflection as convolution: Miller & Hoffman 84, Greene 86, Cabral et al. 87,99
- Reflection as frequency-space operator: D'Zmura 91
- Lambertian reflection is convolution: Basri Jacobs 01

Our Contributions

- Explicitly derive frequency-space convolution formula
- Formal Quantitative Analysis in General 3D Case

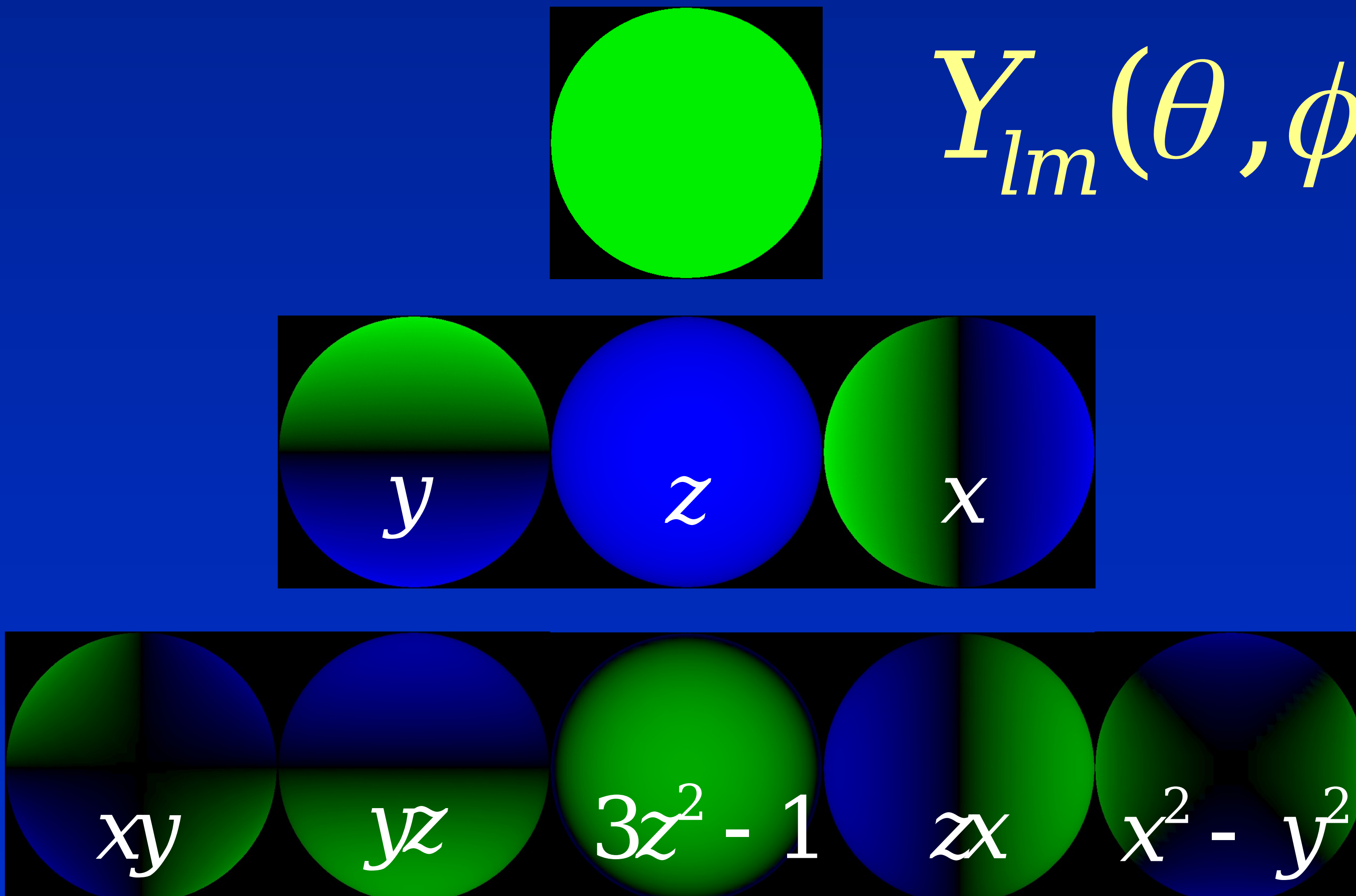
Spherical Harmonics (3D)

$$Y_{lm}(\theta,\phi)$$

0

1

2



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-2 -1 0 1 2

Dual Representation

Diffuse BRDF: Filter width small in frequency domain

Specular: Filter width small in spatial (angular) domain

Pr Rep tion ang
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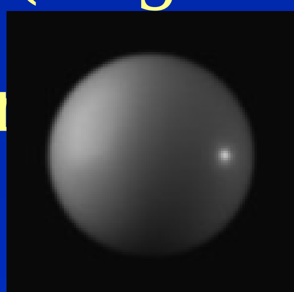

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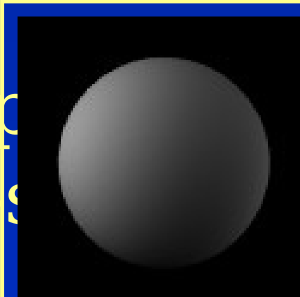
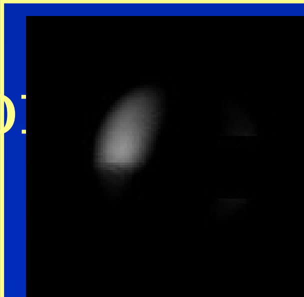


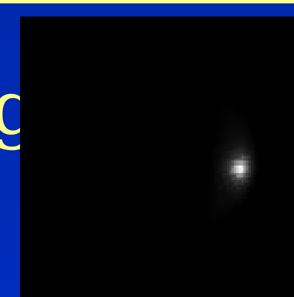
B_d
diffuse

+



$B_{s,slow}$
slow specular
(area sources)

+



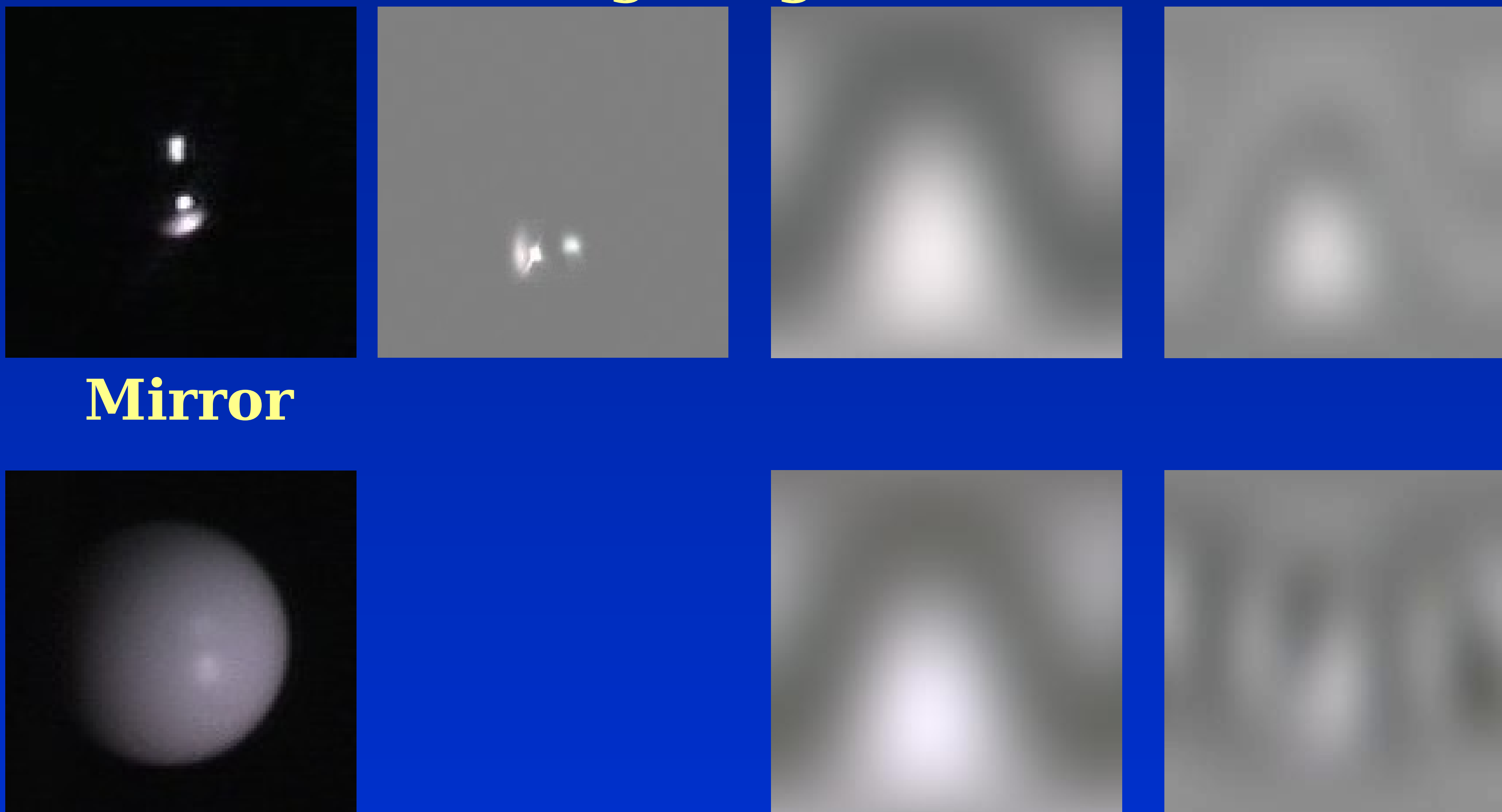
$B_{s,fast}$
fast specular
(directional)

Frequency

Angular Space

Inverse Lambertian

True Lighting Sum l=2 Sum l=4



Mirror

Teflon

Other Papers

- Linked to from website for this paper
  - http://graphics.stanford.edu/papers/invrend/
- Theory
  - Flatland or 2D using Fourier analysis [SPIE 01]
  - Lambertian: radiance from irradiance [JOSA 01]
- Application to other areas
  - Forward Rendering (Friday) [SIGGRAPH 01]
  - Lighting variability object recognition [CVPR 01]